Institute of Physics Publishing Journal of Physics: Conference Series **2** (2004) 165–172
doi:10.1088/1742-6596/2/1/021 Ninth International Symposium on Electron Beam Ion Sources and Traps

Determining the Acceptance of the Brookhaven EBIS Test Stand for Primary Ions by Computer Simulation*

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Abstract. We report on computer studies to determine the acceptance of the Electron Beam Ion Source Test Stand (EBTS) at BNL. Knowledge of the acceptance is a useful guide in selecting a source of primary ions, and in designing a transfer line which best matches the primary ion beam to the acceptance of the EBTS. In this work, an ion beam with suitable parameters is tracked out of the EBIS, to a plane where knowledge of the acceptance is wanted. The emittance of the extracted beam in this plane gives a starting point for determining a more reliable value of acceptance. The result will be compared with a theoretical estimate.

INTRODUCTION

For a large group of elements, an external ion source is the best way to feed the EBIS trap with low charge state (primary) ions of these elements. An important piece of information for injecting these primary ions into the EBIS is the acceptance of the latter. To maximize injection efficiency, the primary ion source being used should have an emittance comparable to, or less than, the acceptance of the EBIS, and the design of the transport line of the primary beam, from its source to the EBIS, should maximize the overlap of the transverse emittance phase space of the beam and the acceptance phase space of the EBIS.

Figure 1a is a layout of the BNL EBIS test stand (EBTS). Typical axial magnetic field profile and electron beam envelope are shown in the Figure 1b. The simulations involved the section from near the mid-plane of drift tube #8 to the first lens after the ion extractor.

PROCEDURE

The general scheme was to launch ions, Au^{2+} in this study (because the charge state distribution of the MEVVA source considered for use peaks at 2+) into EBTS, in the presence of the space charge of the electron beam. The tracking neglected the space charge of the ion beam. If a particle's track met certain criteria, the particle was

* Work performed under the auspices of the U.S. Department of Energy.

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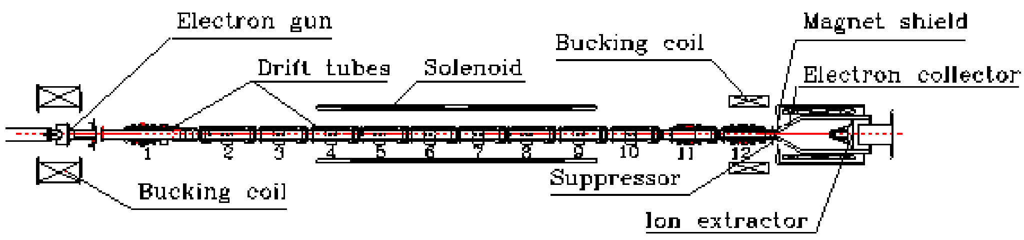
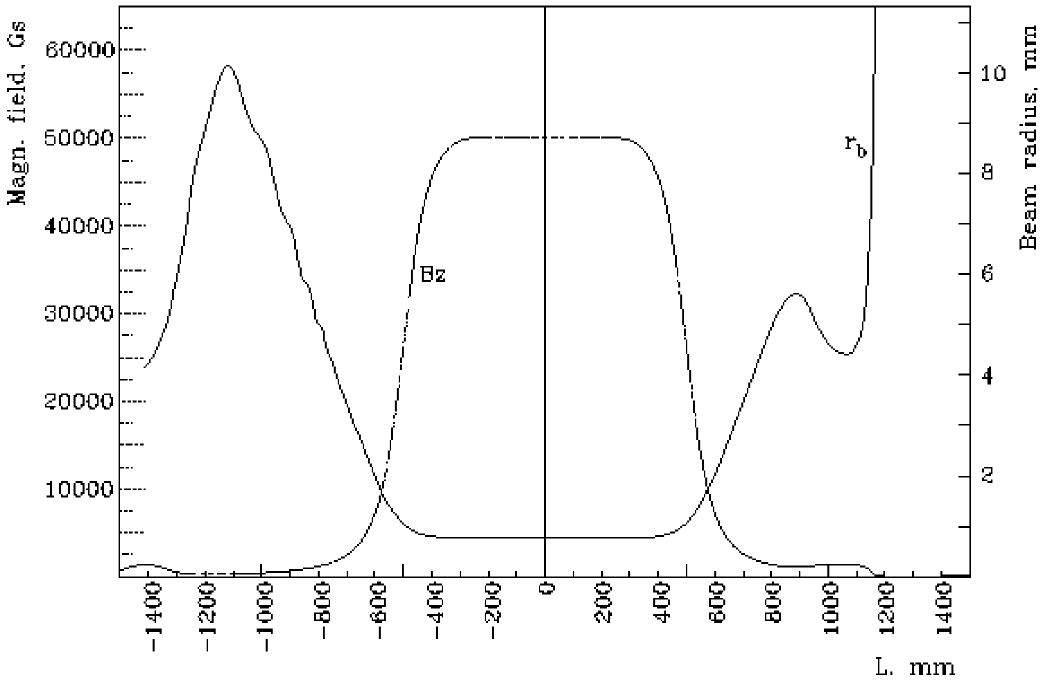


a



b

FIGURE 1. (a) Schematic of EBTS showing drift tubes which are numbered. Tracking was from drift tube 8 to the lens to the right of the extractor. (b) Axial magnetic field profile and typical electron beam envelope.

considered accepted, and its launch coordinates were included in the ensemble of particles used to determine the acceptance. The TRAK program suite from Field Precision[1] was used for the simulations. However, generating randomized launch coordinates and analyzing the very large output files were done using in-house programs.

To make the process more efficient, we first simulated the extraction of a very low energy Au^{2+} ion beam in the solution field of the electron beam, from the trap to the plane where we wish to define the acceptance and Twiss parameters. We argue that the emittance of this beam at the stopping plane is a reasonable initial guess of the acceptance of EBTS.

The following steps were used:

1. Find and save the POISSON solution for the electron beam (9 A on 12/17/2003) from the ion trap to the collector. See Figure 2.
2. Generate launching coordinates – x, y, x′, y′ and kinetic energy, T_i, for ions within the electron beam. T_i was calculated from the ion's starting radius and electrostatic potential energy in the electron beam, such that all ions had the same total energy. Later, additional kinetic energy was given to the ions, to see how the emittance was affected. Typical ion tracks are shown in Figure 3, and phase plots at the stopping plane are shown in Figure 4.
3. As a check of step 2, the momenta of the ions at the end of the tracks were reversed and the ions tracked back into the trap. We expected all of them to make it; about 90% did.
4. Determine ε_{rms} and the Twiss parameters of the extracted ion beam at the stopping plane. When the sign of the Twiss parameter, α**,** is reversed, we have an initial guess of the acceptance.
5. For different multiples of ε_{rms} obtained in the previous step, generate starting coordinates, which are simultaneously within the two transverse ellipses (x,y) defining the acceptance. A typical set of generated points is shown in Figure 5. (The symmetry of EBTS, and EBISs in general, means that the transverse phase properties are the same.) The ions are monoenergtic, since the beam from the primary ion source has no significant energy spread; but simulations with different energies were made (see Figure 7). The ions are launched into EBTS and tracked to the starting plane in step 2. To reduce the size of the output files, due to the very small integration time steps, only every nth step is saved, where n is usually 5 or 10.
6. Analyze the results to determine the acceptance. The criterion used by Wenander[2] to estimate an upper limit of geometrical acceptance of an EBIS, was applied here. It is that injected ions which remain confined within the electron beam – radius r_{beam} - in the trap region (the last 10 cm of the path in this work), were considered accepted, and their launching coordinates defined the acceptance of EBTS (Figure 6). This criterion was later relaxed to consider ions confined within radii larger than r_{beam}, on the grounds that some of these ions might spend a fraction of their time in the electron beam, and thus have a small but finite probability of being ionized.

ANALYSIS AND RESULTS

Emittance, step 2 and Figure 4, and acceptance, step 6 and Figure 7, were calculated using the following equations[3]:

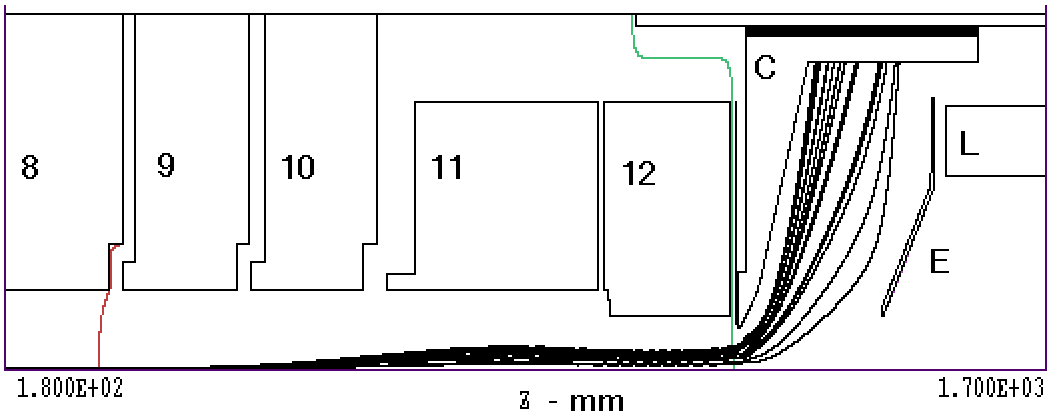


FIGURE 2. 9 A electron beam tracked from the ion trap to the collector. This beam was transported through EBTS on 12/17/2003. The numbered structures represent the drift tubes. C=collector; E=extractor;L=lens.

$$\varepsilon_{rms} = \sqrt{\overline{x^2} \cdot \overline{x'^2} - \overline{(x \cdot x')}^2}$$
$$\alpha = -\overline{x \cdot x'} / \varepsilon_{rms}$$
$$\beta = \overline{x^2} / \varepsilon_{rms}$$
$$\gamma = \overline{x'^2} / \varepsilon_{rms}$$

The ion tracks and phase space plot at the stopping plane are shown in Figures 3 and 4, respectively. In Figure 4, the x and y plots are essentially identical, because of the

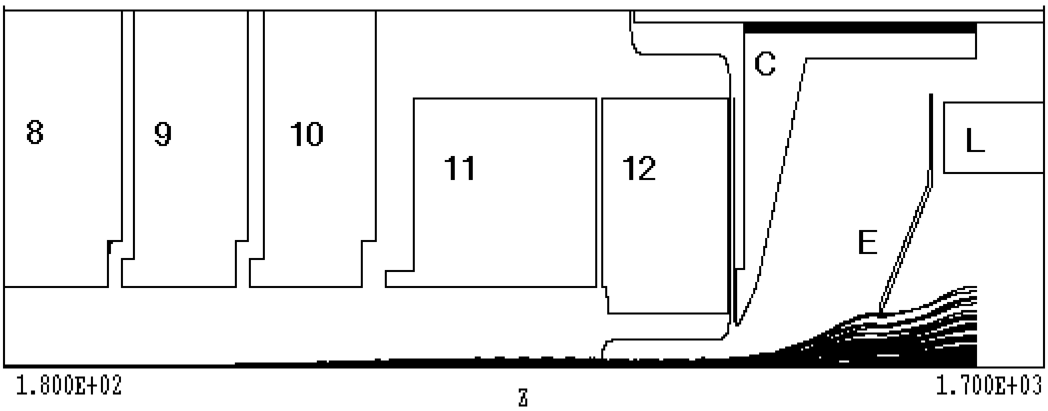


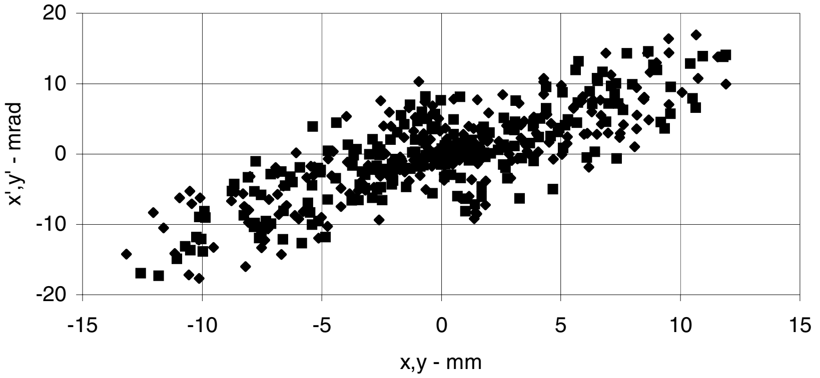
FIGURE 3. A set of ion tracks from drift tube 8 (left) to lens. The shapes of the equipotentials are due to the electron beam solution. The electrodes are the same as in Figure 2.

symmetry of the problem, hence the analysis is done for only the x– plane. The emittance analysis gave the following:

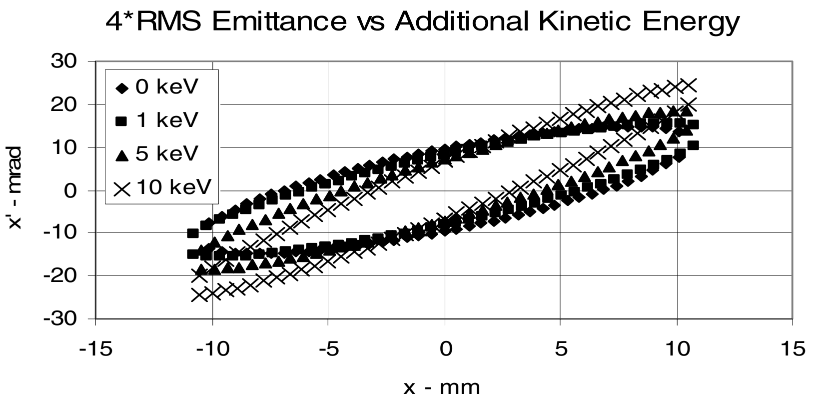
$\varepsilon_{rms} \cong 25\pi$ mm-mrad. α = -1.32, β = 1.37 mm/mrad, γ = 2.0 mrad/mm. When the sign of α is reversed, these parameters represent the approximate acceptance ellipse.

A set of starting points generated for a much larger acceptance ellipse - 200π mm-mrad ($8*\varepsilon_{rms}$) – is shown in Figure 5. The kinetic energy of the ions was 22 keV. (Note that, though selected randomly, the pairs x,x′ and y,y′ are simultaneously within both transverse ellipses). The phase space of ions accepted into a cylinder of radius r_{beam}= 0.55 mm, which is the radius of the electron beam in the trap, is plotted in Figure 6. At $2*r_{beam}$, 100% of the ions are accepted, hence the phase space plot is identical to the plot in Figure 5. The rms acceptance into 0.55 mm is 20.4π mm-mrad.

When the 4*rms (81.6π mm-mrad) acceptance ellipse for 0.55 mm, shown in Figure 6, is used to generate tracks to launch into the source, 92% are within 0.55 mm (100% expected), and 100% are within 1.1 mm. This implies that the ellipse used to generate the launch coordinates is close to a true representation of the acceptance of EBTS. (The **true** acceptance into r_{beam}, by definition, will have 100% of the ions within that radius). **Thus the rms acceptance of EBTS is ~20π mm-mrad.** The acceptance is greater if Wenander's criterion is relaxed.



(a)



(b)

FIGURE 4. (a) Phase plots at the stopping plane. (ℕ) x-x′ and (■) y-y′. 236 out of 250 reached the stopping plane. The ions had no additional kinetic energy. (b) 4*rms emittance ellipses at the stopping plane, when the ion beam is given up to 10 keV of additional kinetic energy.

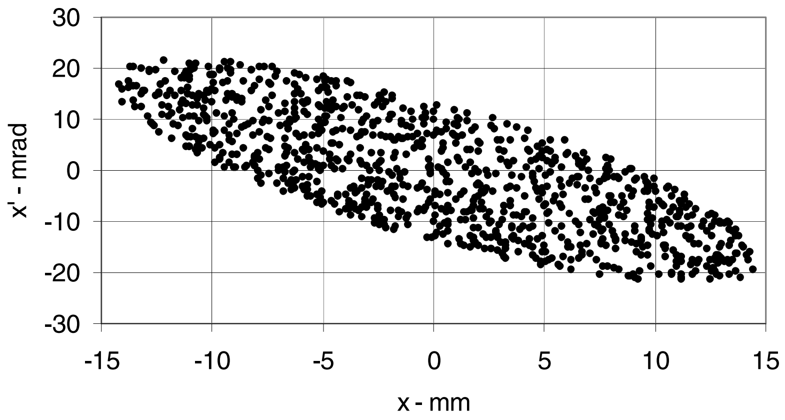


FIGURE 5. Starting x-x′ coordinates for ε_{full} = 200π mm-mrad. 1000 tracks were launched. The kinetic energy was 22 keV. y-y' coordinates were simultaneously within a similar ellipse.

The dependence of the fraction captured, and the acceptance, on radius and the input kinetic energy of the ions is summarized in Figure 7. There is a strong dependence on radius, as should be expected, but a weak one on the input energy.

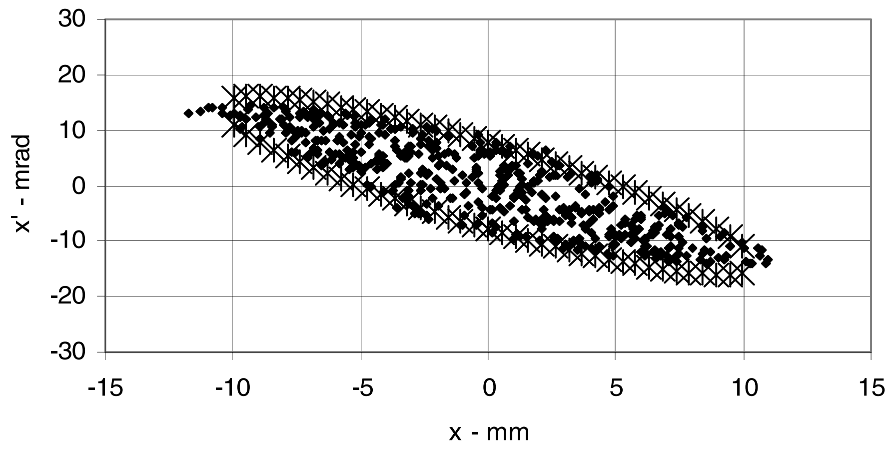


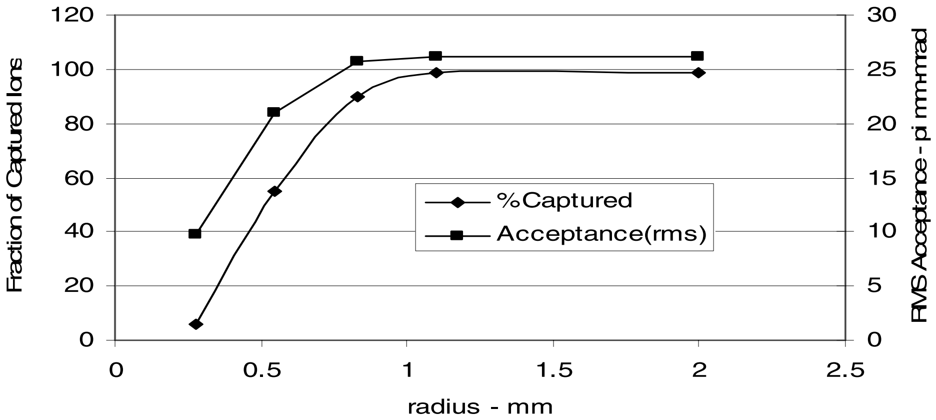
FIGURE 6. Accepted ions from Figure 5 into 0.55 mm radius (50% captured). The ellipse drawn represents 4 times the rms acceptance.

To demonstrate the efficacy of first launching ions out of EBTS to obtain an initial guess of the acceptance, 5000 ions were launched into it from a 500π mm-mrad (20*ε_{rms}) upright ellipse (25 mm x 20 mrad). Only about 2% of these ions were captured within r_{beam}. This should be compared with 50% capture when the starting acceptance ellipse is 8*ε_{rms}. Thus long computer runs are avoided and the results are statistically better.

Evaluating Wenander's expression for EBTS – see the appendix, with B=5 T, we obtain a **total** acceptance of 165π mm-mrad. This is twice the 4*rms value of approximately 80π mm-mrad obtained in this work.

DISCUSSION

We have demonstrated that it is possible to determine the acceptance of an EBIS by tracking large numbers of ions into the trap of the EBIS. The solution is obtained much faster, if a low energy ion beam of the same species is first tracked out of the source. The emittance of this beam provides a reasonable guess of the acceptance.



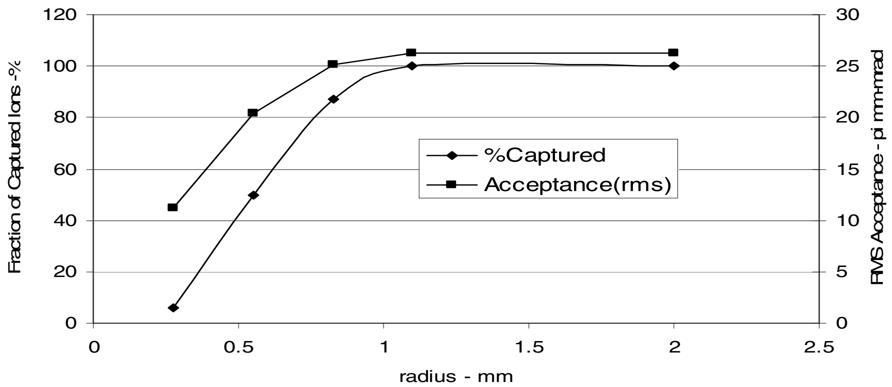


FIGURE 7. The radial dependence of the acceptance of EBTS for injection energies of 21 keV (upper) and 22 keV (lower).

The results obtained here are below the upper limit predicted by Wenander's treatment. The method also gives the Twiss parameters of the acceptance.

With this method one can readily examine how different factors influence the acceptance, although that has not been done here.

The acceptance obtained for radii greater than the electron beam radius should be used with care. The analysis does not tell which fraction of these ions cross the electron beam, and, if they do, how much time they spend in it. We are, after all, interested in acceptance that leads to charge multiplication of ions.

EBIS is also a candidate for use in fission fragment accelerators[4], and detailed studies of acceptance, among other things, will be required.

APPENDIX

Wenander's equation for the maximum geometrical acceptance, α_{max}, is:

$$\alpha_{\max} = \pi \frac{r_{beam}}{\sqrt{2U_{ext}}} \cdot \left[Br_{beam} \cdot \sqrt{\frac{q}{m}} + \sqrt{\frac{qB^2 r_{beam}^2}{4m} + \frac{\rho_l}{2\pi\varepsilon_o}} \right]$$

where

r_{beam} = electron beam radius (m) 0.55 mm
U_{ext} = ion injection potential (V) 11000 V
Q/m = charge-to-mass ratio of the ion species (C/kg) $0.01*\eta_{proton}$
ρ_l = electron beam charge per meter (C/m) 9 A, 25 kV on drift tube
B = trap magnetic field (T) – 5 T

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